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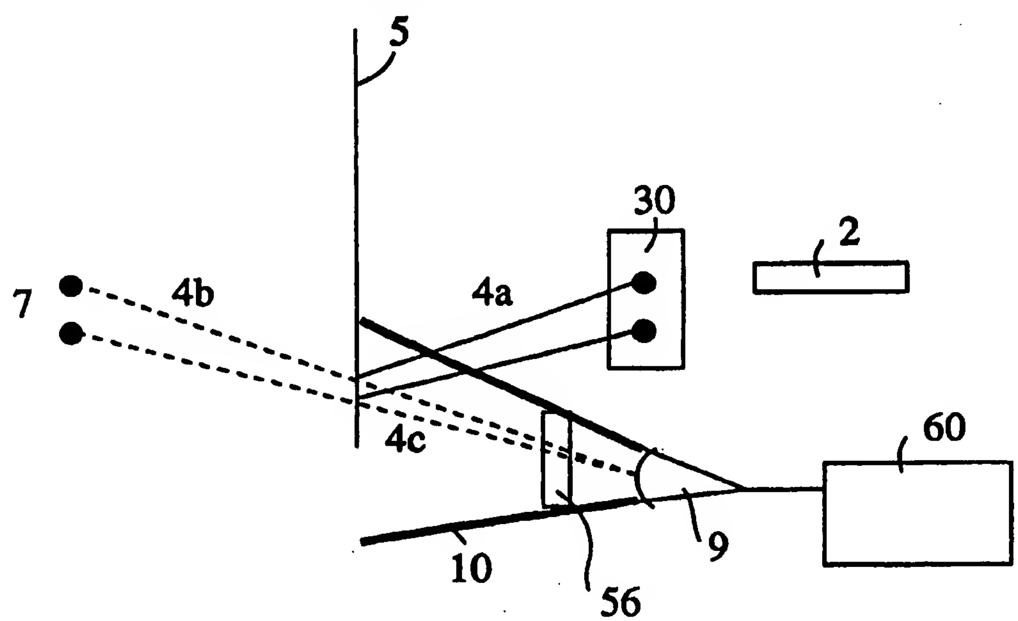

(57) Abstract

A system and method for imaging reflective surfaces are disclosed wherein a diffused light source having a predetermined frequency range and in a predetermined pattern is directed toward the reflective surface. The light reflecting off the surface passes through a filter for filtering out ambient light and reaches a detector. The detector detects the light. Using triangulation with two points within the pattern, a microprocessor determines a distance to an image formed behind the reflective surface. The microprocessor also calculates a distance to the reflective surface in dependence upon the distance to the image and the locations of the diffused light source and of the detector. Alternatively, two detectors are used, requiring a point source of diffused light.

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System and Method for Capturing a Range Image of a Reflective Surface

Field of the Invention

The invention relates to three dimensional (3-D) computer vision and more particularly to three dimensional imaging of objects having reflective surfaces.

Background of the Invention

Human vision relies on experience and stereoscopic vision to determine ranges of objects. Each of two eyes capture an image from locations offset by a predetermined distance, and the brain determines a range to at least an object within a field of view. When peering into a mirror, a person sees images within the mirror of objects that are outside the mirror. Stereoscopic vision establishes a distance to the images that is substantially the distance light travels from the objects to the person's eyes. As such, the English language has an expression "tricks with mirrors" wherein mirrors are used to alter a physical space. For example, placing mirrored tile on a wall in a small room, makes the room appear much larger.

Stereoscopic systems similar to human vision have been proposed for computer vision with applications in measurement, testing, robotics, modeling, manufacturing, navigation, and so forth. It is the very breadth of applications for computer vision that has made them popular both in terms of research and adoption.

Two popular techniques currently in use for optical ranging of a target surface are known, respectively, as the standard optical triangulation system and the Biris (bi-iris) system, the latter employing an apertured mask in a converging lens system of an imaging device having a position sensitive detector, e.g. a CCD camera.

These systems are described and compared in a paper entitled "Practical Considerations for a Design of Industrial Systems, SPIE Vol. 959, 1988, pp 225-246 by F. Blais et. al., and also in. "Optical Range Image Acquisition for the Navigation of a Mobil Robot, " published in the proceedings of the 1991 IEEE International Conference on Robotics and Automation, Sacramento, California, April 9-11, 1991 by F. Blais et. al.

A further article of note is "Active, Optical Range Image Sensors," by Paul J. Besl, Machine Vision and Applications (1988) 1:127-152. All these documents are hereby incorporated herein by reference.

A sample machine vision system is disclosed in U.S. Patent number 5, 270, 795 entitled Validation of Optical Ranging of a Target Surface in a Cluttered Environment, in the name of F. Blais. The system comprises a collimated laser light source and an image capture means for capturing light diffused by opaque surfaces. It merges the features of standard optical triangulation systems and those of Biris systems. The system uses a laser light source and a detector having two irises distanced apart. Light from the laser diffused from opaque surfaces is detected at the detector through each of the two irises. The resulting images are correlated to determine range. Unfortunately, when surfaces are reflective or transparent, collimated light sources are often reflected as collimated beams missing the image capture means. As such, many range sensing means relying on optical range sensing are limited to substantially opaque surfaces. The content of U.S. Patent number 5, 270, 795 to F. Blais is hereby incorporated herein by reference.

In U.S. Patent 4,645,347 titled Two Dimensional Imaging Device in the name of Rioux, a mask aperture having a plurality of apertures therein is described for use in imaging. Such a mask is cost effective in reducing a number of required detectors in an imaging system and for reducing effects caused by vibration.

Object of the Invention

In an attempt to overcome these and other limitations of the prior art, it is an object of the present invention to provide a system and a method for ranging reflective surfaces and for determining a geometry for said surfaces.

Summary of the Invention

In accordance with the invention there is provided a method of measuring a distance from a first location to a reflective surface. The method comprises the steps of:

directing diffused light toward the reflective surface forming an image therein;

using a range imaging means having a detector, measuring a distance from the detector to the image; and

determining the distance to the reflective surface based on a known relationship between the location of a diffused light source, the location of the detector and the distance from the detector to the image.

In accordance with the invention there is provided a method of measuring a distance to a reflective surface comprising the steps of:

projecting toward the reflective surface a pattern of diffused light forming an object;

using an imaging means comprising a detector, said detector having a known spatial relation to the object, receiving some of the projected light reflected off of the reflective surface and forming an image of the object;

using a processing means, determining a range to an image of the object; and

using the processing means, determining a distance to the reflective surface based on the known spatial relation and the image range.

In accordance with another aspect of the invention there is provided an imaging system comprising

a diffused light source for directing diffused light toward a surface and for forming at least an image therein;

an imaging means comprising at least a detector for receiving diffused light reflected from the surface and having a predetermined spatial relation with the diffused light source; and

image processing means for determining a distance from the system to an image of the at least an image and for determining a distance from the system to at least a location on the surface from which diffused light is reflected.

An advantage of the present invention is the ability to model reflective surfaces using an optical range measurement device.

Brief Description of the Drawings

Exemplary embodiments of the invention will now be described in conjunction with the following drawings, in which:

Fig. 1 is a simplified diagram of a prior art imaging device imaging a reflective surface;
Fig. 2 is a simplified diagram of a prior art imaging device failing to image a reflective surface;
Fig. 3 is a simplified diagram of a device according to the present invention imaging a reflective surface;
Fig. 4 is a simplified diagram of a device according to the present invention imaging a planar reflective surface and indicating the effect of a field of vision upon a detector;
Fig. 5 is a simplified diagram of a device according to the present invention incorporating two detectors and a single diffused light source;
Fig. 6 is a simplified diagram of a device according to the present invention incorporating two detectors and two diffused light sources;
Fig. 7 is a simplified diagram of a device according to the present invention incorporating three detectors and a diffused light source;
Fig. 8 is a simplified diagram of a device according to the present invention incorporating two detectors and two diffused light sources;
Fig. 9 is a simplified diagram of a device according to the present invention incorporating a plurality of detectors and a single diffused light source and imaging a transparent substrate having a predetermined non-zero thickness;
Fig. 10 is a simplified diagram of a device according to the present invention imaging a reflective surface that is non-planar;
Fig. 11 is a diagram showing a triangulation method of determining image range;
Fig. 12 is a simplified diagram of a Biris range system employing a single Biris detector and four diffused light sources; and

Fig. 13 is a flow diagram of a method of determining distance and reflective surface geometry according to the present invention.

Detailed Description of the Invention

Reflective surfaces reflect incident light at an angle equal to the angle of incidence. In Fig. 1 is shown a reflective surface **5** with an object in the form of a collimated laser light source **2** having an iris with a predetermined shape **3**, and a detector **9**, on a first side thereof and according to the prior art. On a second side thereof is an image **7** of the object. Once a range for a reflective surface **5** has been determined, a detector **9** and a collimated laser light source can be aligned (as shown in Fig. 1) to allow for the detector to capture a reflected collimated beam **4c**. Unfortunately, absent knowledge of range, orientation, and characteristics such as shape, alignment is not possible and detecting the collimated reflected beam is a matter of chance.

Referring to Fig. 2, a reflective surface **5** in the form of a polished mirror is shown having an object, a collimated laser light source **2** having an iris with a predetermined shape **3**, and detector **9** according to the prior art on a first side thereof and having an image on a second side thereof. Paths of light are shown for light from the collimated laser light source **2**. As can be seen, light reflected by the reflective surface **5** misses the detector **9** and therefore is not used in determining a range for the surface **5**. Alternatively, when light is diffused at the object, it is imaged by the detector **9** and is used for determining a range. Resulting range images treat reflective surfaces and transparent surfaces as holes or worse yet, inconsistently treat them as either holes or, when alignment happens to be appropriate, as surfaces. Further, the number of diffused and reflected signals reaching a detector leads to inconsistent range detection.

Referring to Fig. 3, an embodiment of the present invention is shown opposite a reflective surface **5** in the form of a highly polished mirror. A laser light source **2** is diffused by diffusion means **30** producing a recognizable pattern of light and dark (two diffusing circles and an opaque frame). Diffusion means **30** acts as diffusing irises and results in a plurality of objects. A detector **9** in the form of a CCD is positioned for

receiving light from the objects once the light is reflected off a reflective surface. The detector **9** is provided with a frequency selective filter means **56** for filtering frequencies other than a predetermined range of frequencies. This allows use of the invention in lighted conditions. Alternatively, the filter means filters ambient light of predetermined frequencies. Further alternatively, no filter is used. Preferably, a diffused light source provides illumination of a large percentage of a field of view for the detector. Preferably, diffused light source thickness is small to result in sharp images at the detector **9**.

In operation, light emitted by the laser **2** is diffused by the diffusion means **30**. The diffused light reflects off the reflective surface **5** and reaches the detector **9**. It will be clear to those skilled in the art that diffused light is likely to reach the detector **9** whereas collimated light would be less likely to reach the detector **9** in sufficient quantities. A range detection algorithm executed within a processing means **60**, determines a distance between the detector 9 and images 7 of the objects (diffusion means) **30**. The processing means **60** then determines a range between the detector **9** and the reflective surface **5** in dependence upon the known relative locations of the objects **30** and the detector **9**. Further, when sufficient images 7 are imaged by the detector **9** and in dependence upon a recognizable pattern of the objects **30**, a surface shape of the reflective surface **9** is determined.

In order to determine a range to an image at least two data points are required. These points can be acquired by projecting at least two light sources, by projecting an object with at least two discernible features, by capturing an image with at least two detectors or by capturing images with a detector provided with two irises (Biris). Each of these systems is discussed in detail below.

Referring to Fig. 4, using a collimated light source and a diffuser, allows light within a narrow band of frequencies to be projected and to form several objects **31-36**. Several objects result in several images **71-76** in reflection. Unfortunately, many detectors have small fields of view **10** of for example 30 degrees. 6 objects **31-36** form 6 images **71-76** in a mirror **5** but only objects 33, 34, 35, and 36 are detected by the detector **9.** The images are all visible to a human eye in a location chosen for a detector **9**. Unfortunately,

due to a field of view **10** associated with the detector **9**, the images **71** and **72** are not detected by the detector **9**. Since a range is calculated to each image and there is a known distance between each object and the detector **9**, a determination of which image is associated with each object is possible. This determination is then used to accurately determine a distance to the reflective surface **5**.

To distinguish between associated objects and images, some calculations are performed. A distance D_i is measured between the detector **9** and each image. Each distance corresponds to a series of potential locations and orientations of the reflective surface **5**. The resulting equation for each distance D_i is a simple triangulation with an unknown angle at a vertex thereof. Thus, the distance D_i is equal to the distance of **4a** added to the distance of **4b**. The distances of 4a and 4b are interrelated by the distance from the object to the detector K (shown in Fig. 10). A discussion of the calculations required and the definitions of K, K1,.. is presented later.

Associating an image for which a distance is to be calculated with an object determines a value for K. When the association is correct, a triangle is formed with a known base K and an unknown height. Relying on the rules of geometry, a unique triangle has been defined. In dependence upon the oricntation of the base and an angle defined by a vertex of the triangle, surface orientation is determined. Therefore, by determining a distance to an image and using the known distance from the detector to an associated object, a distance to an imaged point on a surface is determined. The orientation of the surface can be determined using two measurements.

Unfortunately, as shown in Fig. 4, some images are not detected. When this occurs, images and objects must be associated correctly in order to determine an accurate measurement of distance. A method of associating images and objects is to project objects that are distinguishable one from the other. Another method is to project objects spaced apart such that two objects associated incorrectly with images will result in the determination of different surfaces; correlating determined surface location and orientation allows for verification of results.

Applying this latter method to imaging a reflective surface is now described. An image is captured by the detector **9** (shown in Fig. 4) of a plurality of images. The number of images (4) is determined and a preliminary association is made. A distance to each image and a corresponding surface is determined. Each surface is then compared to determine whether or not the determined surfaces are consistent. Associating the images with different objects is performed in order to determine a consistency of other associations. Once sufficient associations have been made, a most consistent surface is selected as the surface measured. When the surface or the detector is moving, the consistency of the surface is measured against other surface shape and distance determinations.

When the reflective surface **5** has an irregular shape or is curved, further data points are required to resolve surface geometry. A method of doing so is shown in Fig. 10 and described later.

Using a single diffused light source in the form of an LED, a single object exists. By capturing an image with each of at least two detectors, A distance to the image can be ascertained. Referring to Fig. 5, an embodiment of the present invention is shown opposite a flat reflective surface. A laser light source **2** is diffused by diffusion means **30** producing a recognizable pattern of light and dark. The diffusion means **30** acts as an object. A plurality of detectors **9a** and **9b** in the form of CCDs are positioned proximate the object. The detectors are provided with a frequency selective filter means **56** for filtering frequencies other than the laser frequency. Alternatively, the filter means filters ambient light at predetermined frequencies. Further alternatively, no filter is used. The use of two detectors results in the capture of two data points for the image (as is shown in Fig. 5) and allows for triangulation to be employed.

Referring to Fig. 6, a system provided with 2 detectors and 2 diffused light sources is shown. The system results in the acquisition of 4 data points. Such a system is useful for range determination and for surface modeling of the reflective surface **5**. For each image, a distance and surface orientation is calculated. Due to the increased number of data points, a solution is now possible (and unique) for surface distance, surface

orientation, and surface curvature (over a section of the surface). Moving the detectors or the surface allows image capture of the entire surface and allows for surface modeling. Preferably the relative motion is accurately measured to ensure accurate modeling.

Referring to Fig. 7, an embodiment wherein a single diffused light source projects images to each of 3 image capture means is shown. In principal, the device operates similarly to that of Fig. 6. Triangulation is achieved between each pair of points (three different pairs) to determine information relating to surface distance, surface geometry, and surface orientation.

In Fig. 8, a similar system to that of Fig. 6 is shown wherein the light sources are diffused light sources in the form of LEDs **21**. Alternatively, the light sources **21** can be regular diffused light sources (bulbs) or other diffused lighting means. The elimination of a laser light source reduces the overall cost of the system. When using limited frequency LEDs, a frequency dependent optical filter may be employed to filter out ambient light from light reaching the detector.

Transparent surfaces tend to be reflective in part. In Fig. 9, a transparent surface **50** in the form of a glass plate is shown. Using the present invention, both a surface geometry and a thickness can be determined for the glass plate. As is noted in dotted line at **4d**, a further image is detected having a different distance (in this case D_i plus twice the thickness of the glass plate). A processing means **60** resolves the images 7 and **7d** and calculates image distances in order to determine plate thickness and surface geometry.

Referring to Fig. 10, an embodiment of the present invention shown opposite a reflective surface with regular curved geometry is shown. A laser light source **2** is diffused by diffusion means **30** producing a recognizable pattern of light and dark. The diffusion means **30** acts as a plurality of objects. Detectors **9a** and **9b** in the form of CCDs are positioned proximate the objects **30**. Alternatively, the detectors **9a** and **9b** are positioned in a location having a known spatial relation to a location of the objects **30**. The detectors **9a** and **9b** are provided with a frequency selective filter means **56** for

filtering frequencies other than the laser frequency. Alternatively, the filter means filters ambient light of predetermined frequencies. Further alternatively, no filter is used.

Returning to Fig. 9, In operation, light emitted by the laser **2** is diffused by the diffusion means **30**. The diffused light is reflected from the reflective surface **5** and reaches the detectors **9a** and **9b**. It will be clear to those skilled in the art that diffused light will reach the detectors **9a** and **9b** whereas collimated light would be less likely to reach the detectors **9a** and **9b** in sufficient quantities. A range detection algorithm executed within a processing means **60**, determines a distance between the detectors **9a** and **9b** and an image **7** of the objects (diffusion means) **30**. Where, as in this instance, the reflective surface is non-linear, the image **7** is distorted relative to the objects **30** and/or magnified relative to the curvature of the surface. The processing means **60** correlates objects 30 and images 7. Alternatively, points on an object (known) are correlated with points on a captured image (reflected). Using the known spatial relation between the detectors **9a** and **9b** and the objects **30**, the processing means determines a distance to at least some of the points on the reflective surface **5**. Locations of these points are then used to determine a surface geometry for the reflective surface **5** and therefore orientation and magnification of the curved surface can be determined. At least 3 captured images are required to determine surface geometry. Preferably, more images are captured. Further images at different angles or from different known locations allow for the construction of a geometric model of the reflective surface **5**. Alternatively, a large object with a discernible pattern is used to model the entire surface. Further alternatively, the diffused light source is stationary and only the detectors **9a** and **9b** move. In this last embodiment, the diffused light source's pattern is used to determine detector angle or location; image overlap is used to construct a model of the reflective surface 5.

Referring to Fig. 11, calculations used in determining a distance to a detected image are shown. A detector is spaced a distance K1 from a first object and a distance K2 from a second object. The objects are spaced apart by a distance of K and the two objects and the detector are co-linear. Therefore, $K = |K2 - K1|$. The detector detects images of each of the first and second objects. The images are at angles of α and θ, respectively,

Between thc images of the first and second objects is a distance K similar to that distance between the objects themselves. Therefore, a triangle is formed with a known base and a known angle opposite the base. This results in a determined triangle. Once determined the values of D1 and D2 are calculated using trigonometric functions or other known methods.

A second series of triangles is now formed in which the bases are K1 and K2 respectively. Angles of a corner of each triangle adjacent the base are known. The distance around the perimeters of the two triangles are D1 + K1 and D2 + K2, respectively. This is known because the optical paths from the detector to the images D1 and D2 are equal in length to the optical path from each of the first object and the second object, respectively. As the light travels in a substantially straight line from the object to the reflective surface and from the reflective surface to the detector, the distance D1 is equivalent to the distance in traversing two sides of a triangle; the third side of the triangle has a length K1. Similarly, D2 is equivalent to the distance in traversing two sides of a triangle; the third side of the triangle has a length K2.With this information the two triangles can be evaluated to determine all distances and thereby measure a distance to a point on a substantially flat reflective surface. This method of determining range is known in the art as photogrammetry.

Referring to Fig. 12 an embodiment of the invention using a Biris detector 9 having two apertures 91 and 92, a lens 96, and a CCD 97 and 4 diffusing light sources **3** is shown. Existing implementations of Biris systems weight standard plane of light range measurement contributions with Biris contributions to increase accuracy of a range measurement. A plane of light measurement forms a large part of a range measurement since it relies on a large triangulation base.

When surface curvature is small, because of a small separation between apertures **91** and **92** in the detector **9** mask a range is calculated by the system. The distance between the apertures **91** and **92** is referred to as b. Further, an angle of incidence of light is determined in dependence upon a point on a CCD within the detector **9** where the light is incident. The point is referred to as p. From these two values (p and b) range can be

determined (as explained with reference to Fig. 11 and U.S. Patent 5,270, Validation of Optical Ranging of a Target Surface in a Cluttered Environment to F. Blais).

When curvature of a surface is monotonic, range measurements from 2 different profiles are used to evaluate the curvature of the surface. Alternatively, p is used as with other curved surfaces. Once a curvature of a surface is known, a relation between b and p becomes known and is used to validate range measurements.

One possible algorithm that includes signal validation and range refinement based on low curvature property of a reflective surface is as follows:

1. for each detected image, compute a range;
2. to each image associate an object;
3. for each image range and associated object, compute a surface range and orientation;
4. evaluate the surface orientation/curvature and range resulting from each computation in step 3 and correlate them;
5. when the computed values do not correlate, associate the images with different objects and return to step 3; and
6. when the computed values correlate, minimize any range surface curvature errors computed in step 3.

In measuring range for curved surfaces compensation for curvature of the surface is applied. The compensation is used because curvature of a reflective surface alters image locations. When curvature is sufficiently small, the surface is treated as a planar surface for each measurement and a curved surface is reconstructed in dependence upon a plurality of range measurements. Alternatively, when the curvature of the surface is not sufficiently small, compensation is required.

For a lens of radius r and index of refraction n, the focal length is

$r=(n-1)f$ (for a mirror $n=-1$).

The distance of the position of the image to the surface is modified by the curvature of the surface; however, the technique to compute the location of the reflective surface assumes a substantially flat surface ($r=\infty$) and therefore, any change in image location results in a corresponding change to a measurement of range. In order to determine curvature for the surface using the above equations, we require its range. In order to determine the surface range using the above equations, we require a known surface curvature. Because both curvature and range are unknown, an iterative approach to converge measured range and curvature to corresponding values. A detailed mathematical explanation of a method employed is presented in Appendix A attached.

Using a system as defined in the present invention, effects of laser speckle are reduced. Smooth reflective surfaces are known to reduce laser speckle. Further, polychromatic light sources may be used, thereby avoiding laser speckle.

Anamorphic lenses may increase camera accuracy while retaining field of view. It will be apparent to those of skill in the art that as laser field of view increases, further constraints are imposed upon dimensions of light sources arrays.

For imaging reflective surfaces with a high degree of curvature, light source and detector location is important. As such, specific light source-detector geometries for high curvature surfaces are employed. This improves a chance that sufficient images will fall within a field of view of a detector, and that those images are correctly associated with objects. Distinguishing between objects can be achieved in many ways. For example, each object (diffused light source) can have a different wavelength or a different shape. Allowing sufficient images to fall within a field of view is a geometrical problem to be solved in dependence upon known criteria regarding a surface.

Referring to Fig. 13, a method of determining distance and reflective surface geometry is shown in a flow diagram. Diffused light is projected at a reflective surface a range for which is to be determined. The diffused light is in the form of at least an object. The diffused light reflects off the reflective surface and is detected by at least a detector.

At least two and preferably at least three instances of reflected light are detected by the at least a detector.

For each instance a range is calculated to an image (as viewed by the at least a detector) of the at least an object. Each image is associated with an object in the form of a diffused light source. The association is estimated and may be incorrect. In dependence upon each association, a range and orientation are calculated for the reflective surface. The calculated ranges and orientations for each image are compared to determine a surface. When a surface results, it is refined by reducing errors in surface range and curvature. When an inadequate surface results, at least an image is associated with a different object and the range and orientation is recalculated. The method continues from the calculation of range and orientation as set out above.

A diffused light source is a primary light source providing diffused light. Alternatively, a diffused light source is a secondary light source transmitting or reflecting light incident thereon in a diffused fashion. A discernible object reflecting some diffused light acts a diffused light source. Further, as described above, the primary source of light need not provide diffused light and, in an embodiment, is a collimated laser light source in conjunction with a diffuser acting as a secondary light source.

Numerous other embodiments of the invention may be envisioned without departing from the scope of the invention.

Appendix A
Range measurement of reflectives surfaces
- Compensation of surface radius: 2D case -

This document evaluates the modifications that are needed to the range data to compensate for the radius of the object surface.

The curvature of the object changes the position of the image of the source. If the curvature is small, then the surface can be considered planar and a direct reflection of the image occurs. If not then the location of the image changes and must be compensated.

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Date	By	Comment
8/20/1996	F.B.	Initial draft (rev II)
8/21/1996	F.B.	Initial draft (rev III)
9/6/1996	F.B.	Use tangential aberations

For a lens or radius r and index of refraction n, the focal length is

$r=(n-1)\cdot$ for a mirror (n=-1): $f=\frac{-1}{2}\cdot$

The distance of the position of the image of the source to the surface is modified by the "focal" of the surface, using the formula:

$\frac{1}{f}=\frac{1}{r\_ls}-\frac{1}{r\_obj}$ $\frac{-2}{r}=\frac{1}{r\_ls}-\frac{1}{r\_obj}$ r_obj is the position of the object

However the technique to compute the location of the surface of the reflective object assumes r=∞ and therefore the change in the location of the image will affect the exact location of the surface.

We need the exact location of the surface to compute its curvature, and vice-versa. The idea is to iteratively converge to the exact surface location, each time computing a new surface curvature and position.

From the range sensor the distance of the image to the camera ric is related to the distance of the camera to the surface using:

$ric=roc+ro$ ci = camera image, co=camera object, oi=object image

The actual method, assuming a flat surface (r=∞) computes the location roc. Assuming r<>∞ (mirror) then

$ric\_m=roc+roi\_$

The sensor measures the modified position of the image ric_r. The compensated position ric is obtained using:

$$\frac{-2}{\infty} = \frac{1}{-r\_ls} + \frac{1}{r\_obj\_} \qquad 0 = \frac{1}{r\_ls} - \frac{1}{r\_obj\_} \qquad r\_ls = r\_obj\_$$

therefore,

$$\frac{1}{feq} = \frac{1}{r\_obj\_m} + \frac{1}{r\_obj}$$

Knowing the normal to the surface: δ, and the angle of the camera, with the position of the image if a mirror was used: yi_m, zi_m

$$\delta = \operatorname{atan}\left[\frac{(ys - yi\_m)}{(zs - zi\_m)}\right] \qquad \phi = \operatorname{atan}\left(\frac{zi}{yi}\right) \qquad \phi = \operatorname{atan}\left(\frac{zi\_m}{yi\_m}\right)$$

The equivalent focal length of the mirror is (using curvature c) $c = \frac{1}{R}$

$$feq = f\_nominal \cdot \cos(\phi - \delta) \qquad f\_nominal = \frac{-R}{2} \qquad f\_nominal = \frac{-1}{2 \cdot c} \qquad feq = \frac{-1}{2 \cdot c} \cdot \cos(\phi - \delta)$$

Furthermore we have

$$r\_obj = \frac{zi - zo}{\cos(\phi)} \qquad r\_obj\_m = \frac{zi\_m - zo}{\cos(\phi)}$$

therefore, using z measurements as reference:

$$\frac{1}{\frac{1}{2 \cdot c} \cdot \cos(\phi - \delta)} = \frac{1}{\left(\frac{zi\_m - zo}{\cos(\phi)}\right)} + \frac{1}{\frac{zi - zo}{\cos(\phi)}} \qquad zi\_m = \frac{(2 \cdot c \cdot zo \cdot zi + 2 \cdot c \cdot zo^2 - \cos(\phi) \cdot \cos(\phi - \delta) \cdot zi)}{(-2 \cdot c \cdot zi + 2 \cdot c \cdot zo - \cos(\phi) \cdot \cos(\phi - \delta))}$$

if

$$c = 0 \qquad zi\_m = z$$

$$\delta = 0 \qquad zi\_m = \frac{(-2 \cdot c \cdot zo \cdot zi + 2 \cdot c \cdot zo^2 - \cos(\phi)^2 \cdot zi)}{(-2 \cdot c \cdot zi + 2 \cdot c \cdot zo - \cos(\phi)^2)}$$

Given

$$zi\_m = zi\_m2 + z \qquad zi = zi2 + z$$

$$zi\_m2 = -\cos(\phi)^2 \cdot \frac{zi2}{(-2 \cdot c \cdot zi2 - \cos(\phi)^2)} \qquad \frac{1}{zi\_m2} = \frac{2}{\cos(\phi)^2} \cdot c + \frac{1}{zi}$$

$$\frac{1}{\frac{1}{2 \cdot c} \cdot \cos(\phi - \delta)} = \frac{1}{\left(\frac{zi\_m - zo}{\cos(\phi)}\right)} + \frac{1}{\frac{zi - zo}{\cos(\phi)}} \qquad zi\_m = \frac{(2 \cdot c \cdot zo \cdot zi - 2 \cdot c \cdot zo^2 + \cos(\phi) \cdot \cos(\phi - \delta) \cdot zi)}{(2 \cdot c \cdot zi + 2 \cdot c \cdot zo + \cos(\phi) \cdot \cos(\phi - \delta))}$$

2nd derivative of a surface vs curvature

I'm trying to evaluate the relationship between the 2nd derivative and the curvature of a surface.

This document is confidential and is the property of:

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Date	By	Comment
9/16/1996	F.B.	Initial draft

The generalized spherical surface is

$$z = \frac{c \cdot r^2}{1 + \sqrt{1 - (1 + k) \cdot c^2 \cdot r^2}}$$

c = curvature of the surface
r = radial coordinate
k = conic constant
k < -1 : hyperbolas, k = -1 : parabolas
-1 < k < 0 : ellipses, k = 0 : sphere
k > 0 : oblate ellipsoids.

Example:

$$z = c \cdot \frac{r^2}{\left(1 + \sqrt{1 - c^2 \cdot r^2}\right)}$$ sphere (k=0) $$c = 2 \cdot \frac{z}{\left(z^2 + r^2\right)}$$

$$z = \frac{1}{2} \cdot c \cdot r$$ parabola (k=-1) Note: $f = \frac{R}{2}$ $f = \frac{1}{2 \cdot c}$ $z = \frac{1}{4 \cdot f} \cdot r$

Taking the derivatives:

$$\frac{dz}{dr} = c \cdot r \cdot \frac{\left(2 \cdot \sqrt{-1 + c^2 \cdot r^2 + c^2 \cdot r^2 \cdot k} - 2i + i \cdot c^2 \cdot r^2 + i \cdot c^2 \cdot r^2 \cdot k\right)}{\left[\left(1 + i \cdot \sqrt{-1 + c^2 \cdot r^2 + c^2 \cdot r^2 \cdot k}\right)^2 \cdot \sqrt{-1 + c^2 \cdot r^2 + c^2 \cdot r^2 \cdot k}\right]}$$

$$\frac{d2z}{dr^2} = c \cdot \frac{\left(4i - 3i c^2 \cdot r^2 - 3i c^2 \cdot r^2 \cdot k + \sqrt{-1 + c^2 \cdot r^2 + c^2 \cdot r^2 \cdot k} \cdot c^2 \cdot r^2 \cdot k - 4 \cdot \sqrt{-1 + c^2 \cdot r^2 + c^2 \cdot r^2 \cdot k} + \sqrt{-1 + c^2 \cdot r^2 + c^2 \cdot r^2 \cdot k} \cdot c^2 \cdot r^2\right)}{\left[\left(1 + i \cdot \sqrt{-1 + c^2 \cdot r^2 + c^2 \cdot r^2 \cdot k}\right)^3 \cdot \left(-1 + c^2 \cdot r^2 + c^2 \cdot r^2 \cdot k\right)^{\left(\frac{3}{2}\right)}\right]}$$

$$\lim_{r \to 0} \frac{d2z}{dr^2} = c$$

For the sphere: k=0

Substituting $c=\sqrt{c2}$ $\gamma=1-c^2\cdot r$ $c2=\frac{(\gamma-1)}{r^2}$

$$\frac{d2z}{dr^2}=c\cdot\frac{\left(\sqrt{-1+c^2\cdot r^2}\cdot c^2\cdot r^2-4\cdot\sqrt{-1+c^2\cdot r^2}+4i-3i\cdot c^2\cdot r^2\right)}{\left[\left(1+i\cdot\sqrt{-1+c^2\cdot r^2}\right)^3\cdot\left(-1+c^2\cdot r^2\right)^{\left(\frac{3}{2}\right)}\right]}$$

$$\frac{dz}{dr}=c\cdot r\cdot\frac{\left(2\cdot\sqrt{-1+c^2\cdot r^2}-2i+i\cdot c^2\cdot r^2\right)}{\left[\left(1+i\cdot\sqrt{-1+c^2\cdot r^2}\right)^2\cdot\sqrt{-1+c^2\cdot r^2}\right]}$$

$$\frac{d2z}{dr^2}=\frac{\sqrt{1-\gamma}}{\left[\gamma^{\left(\frac{3}{2}\right)}\cdot r\right]}\qquad\qquad \frac{dz}{dr}=\frac{\sqrt{1-\gamma}}{\sqrt{\gamma}}$$

Substituting dr from the first derivative

$$d2z=\frac{1}{\left(c\cdot r^2\right)}\cdot\frac{dz^2}{\sqrt{1-c^2\cdot r^2}}$$

From the first derivative:

$$\frac{dz}{dr}=\frac{\sqrt{1-\gamma}}{\sqrt{\gamma}}\qquad \gamma=\frac{dr^2}{\left(dr^2+dz^2\right)}\qquad 1-c^2\cdot r^2=\frac{dr^2}{\left(dr^2+dz^2\right)}\qquad r=\sqrt{\frac{1}{c^2}\cdot\left[1-\frac{dr^2}{\left(dr^2+dz^2\right)}\right]}$$

$$d2z=\frac{1}{\left(c\cdot r^2\right)}\cdot\frac{dz^2}{\sqrt{1-c^2\cdot r^2}}\qquad d2z=c\cdot\frac{\left(dr^2+dz^2\right)^{\left(\frac{3}{2}\right)}}{dr}$$

$$c=\frac{d2z}{\left(dr^2+dz^2\right)^{\left(\frac{3}{2}\right)}}\cdot d$$

Rewritten in a more "usefull" format

$\frac{d2z}{dr^2}=d2z\_$ $\frac{dz}{dr}=dz\_$ i.e. $d2z=d2z\_r\cdot dr$ $dz=dz\_r\cdot d$

$$c=\frac{d2z\_r}{\left(1+dz\_r^2\right)^{\left(\frac{3}{2}\right)}}$$

Claims

What is claimed is:

1. A method of measuring a distance from a first location to a reflective surface comprising the steps of:

directing diffused light toward the reflective surface to form a first image therein;

using a range imaging means having a detector to measure a distance from the detector to the first image formed by the diffused light; and

determining the distance to the reflective surface based on a known relationship between the location of a diffused light source, the location of the detector and the distance from the detector to the first image formed in the reflective surface.

2. A method of measuring a distance to a reflective surface as defined in claim 1 wherein the distance from the detector to the first image is determined in dependence upon detecting the first image with a plurality of detectors.

3. A method of measuring a distance to a reflective surface as defined in claim 2 wherein the plurality of detectors is at least 3 detectors and, wherein the method further comprises the step of determining a surface geometry of the reflective surface.

4. A method of measuring a distance to a reflective surface as defined in claim 1 wherein the first image and at least another image are formed in the reflective surface, and, wherein the method further comprises the step of:

detecting the at least another image with the detector;

and wherein the distance from the detector to the first image is determined in further dependence upon the detected at least another image.

5. A method of measuring a distance to a reflective surface as defined in claim 4 wherein the plurality of images is at least 3 images and wherein the method further comprises the step of determining a surface geometry of the reflective surface.

6. A method of measuring a distance to a reflective surface as defined in claim 1 wherein the first image and at least another image are formed in the reflective surface, and, wherein the method further comprises the step of:

using a plurality of detectors having a known spatial relation therebetween to detect the at least another image;

and wherein the distance from the detector to the first image is determined in further dependence upon the detected at least another image and the known spatial relation.

7. A method of measuring a distance to a reflective surface as defined in claim 6 further comprising the step of determining a surface geometry of the reflective surface.

8. A method of measuring a distance to a reflective surface as defined in claim 1 wherein the detector is a Biris detector.

9. A method of measuring a distance to a reflective surface as defined in claim 1 wherein the diffused light forms a plurality of objects, the directed light reflected off of the reflective surface forms a plurality of images, and the range is determined by the steps of:

a) associating each image from the plurality of images with an object from the plurality of objects;

b) using the processing means, for each image, determining a distance to an estimated reflective surface in dependence upon the associated object location, the location of the detector, and said image location;

c) comparing the estimated surface determined for each image with estimated surfaces determined for other images and evaluating the surfaces to see if a substantially same surface is determined;

d) when substantially a same surface is not determined, using a processor, associating each image with a different object from the plurality of objects and returning to step (b); and,

e) when substantially a same surface is determined, using the processor means, correcting the surface in dependence upon each determined surface.

10. A method of measuring a distance to a reflective surface comprising the steps of:projecting toward the reflective surface, a pattern of diffused light forming an object;using an imaging means comprising a detector, said detector having a known spatial relation to the object, receiving some of the projected light reflected off of the reflective surface and forming an image of the object;using a processing means, determining a range to an image of the object; andusing the processing means, determining a distance to the reflective surface based on the known spatial relation and the image range.

11. A method of measuring a distance to a reflective surface as defined in claim 10 further comprising the step of:determining, in dependence upon the range determined for the image and the known spatial relation, a surface geometry and range for the reflective surface.

12. A method of measuring a distance to a reflective surface as defined in claim 10 wherein the pattern of diffused light forms a plurality of objects, the projected light reflected off of the reflective surface forms a plurality of images, and the range is determined by the steps of:

a) associating each image from the plurality of images with an object from the plurality of objects;

b) using the processing means, for each image, determining a distance to an estimated reflective surface in dependence upon the known spatial relation and said image location;

c) comparing the estimated surfaces determined for each image and evaluating the surfaces to see if a same surface is determined;

d) when substantially a same surface is not determined, using a processor, associating each image with a different object from the plurality of objects and returning to step (b); and

e) when substantially a same surfacc is determined, using the processor means, correcting the surface in dependence upon each determined surface.

13. A method of measuring a distance to a reflective surface as defined in claim 10 wherein the pattern of diffused light is formed by projecting collimated light toward the reflective surface and diffusing the collimated light prior to the light reaching the reflective surface.

14. A method of measuring a distance to a reflective surface as defined in claim 10 wherein the projected pattern of diffused light comprises lines of varying lengths.

15. A method of measuring a distance to a reflective surface as defined in claim 10 further comprising the step of filtering ambient light from light reaching the detector.

16. A method of measuring a distance to a reflective surface as defined in claim 10 wherein the imaging means comprises a plurality of detectors.

17. An imaging system comprising:

a diffused light source for directing diffused light toward a surface and for forming at least an image therein;

an imaging means comprising at least a detector for receiving diffused light reflected from the surface and having a predetermined spatial relation with the diffused light source; and

image processing means for determining a distance from the system to an image of the at least an image and for determining a distance from the system to at least a location on the surface from which diffused light is reflected.

18. An imaging system as defined in claim 17 wherein the diffused light source is for directing diffused light of substantially a same wavelength.

19. An imaging system as defined in claim 17 wherein the diffused light source is for forming a predetermined pattern of light and dark.

20. An imaging system as defined in claim 17 further comprising means for determining a surface geometry of the surface in dependence upon the distance.

21. An imaging system as defined in claim 17 wherein the diffused light source comprises a collimated light source and a diffusion means.

22. An imaging system as defined in claim 17 wherein the diffused light source comprises an LED.

23. An imaging system as defined in claim 17 wherein the diffused light source comprises a laser diode.

24. An imaging system as defined in claim 17 further comprising a filter for filtering ambient light from light reaching the detector.

Prior Art

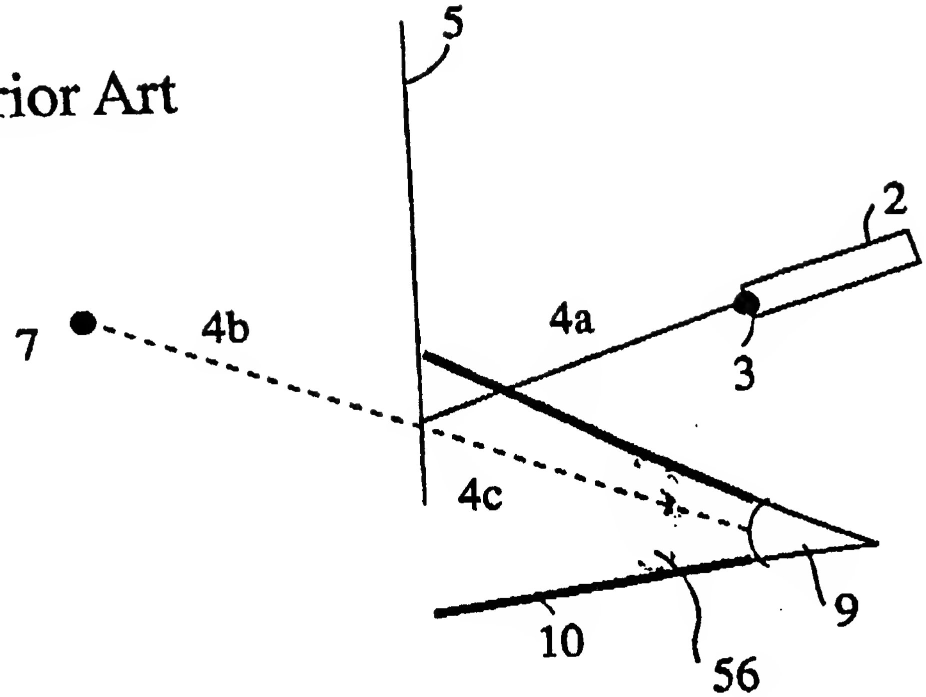

Fig. 1

Prior Art

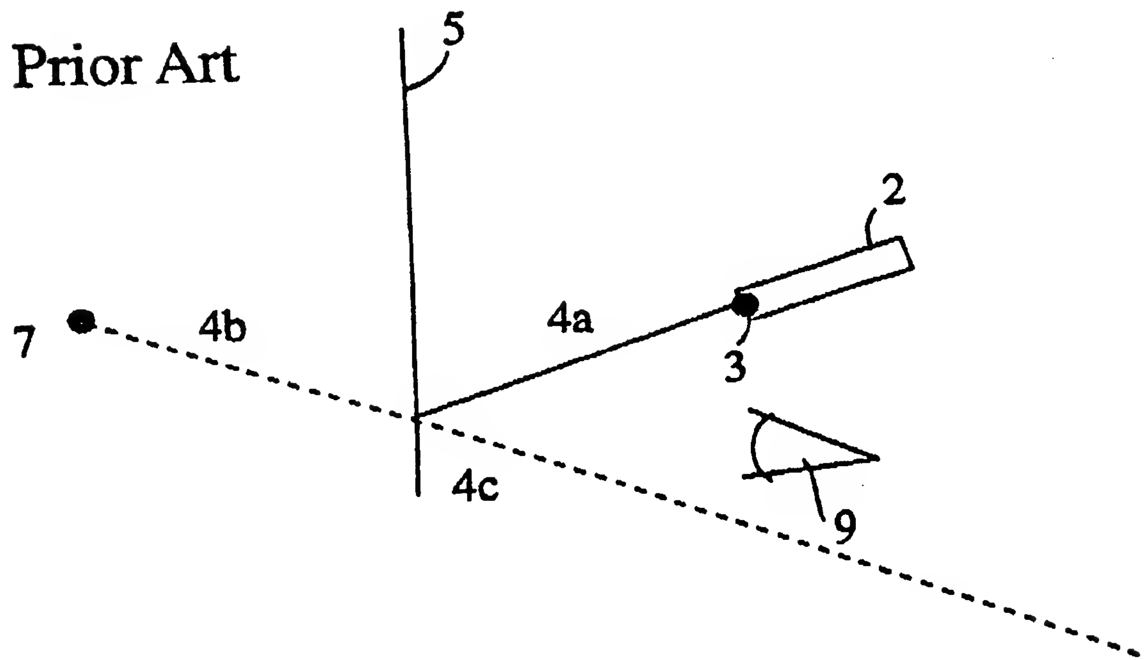

Fig. 2

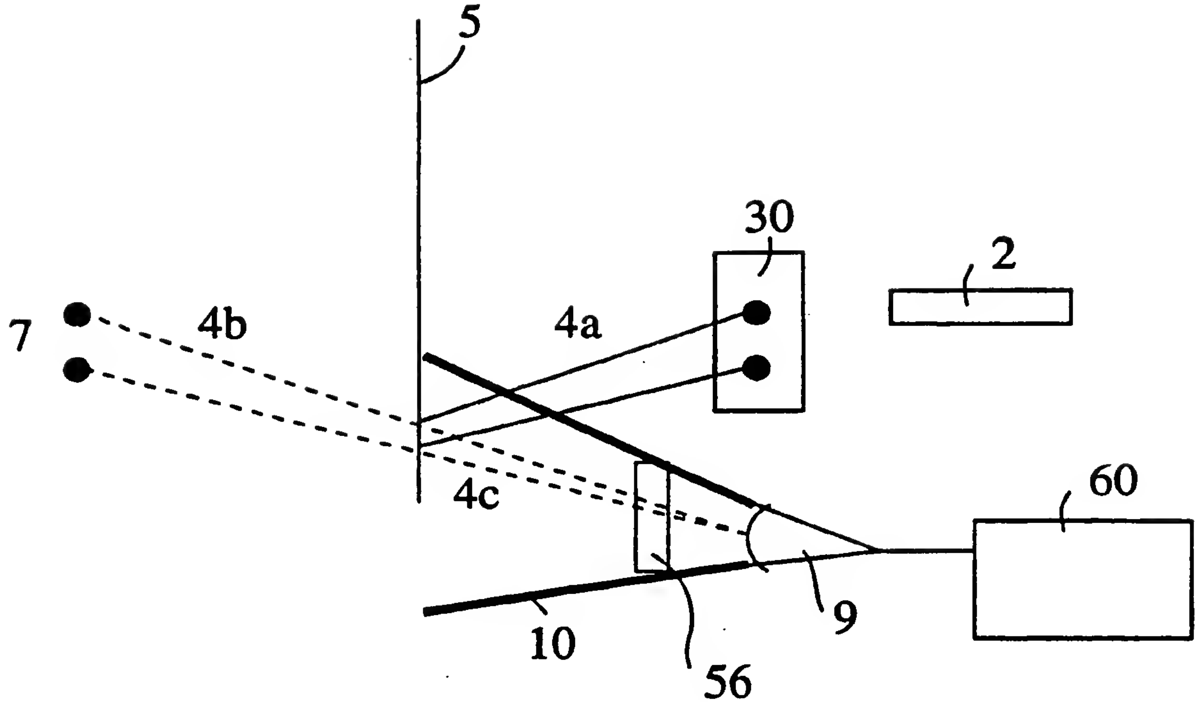

Fig. 3

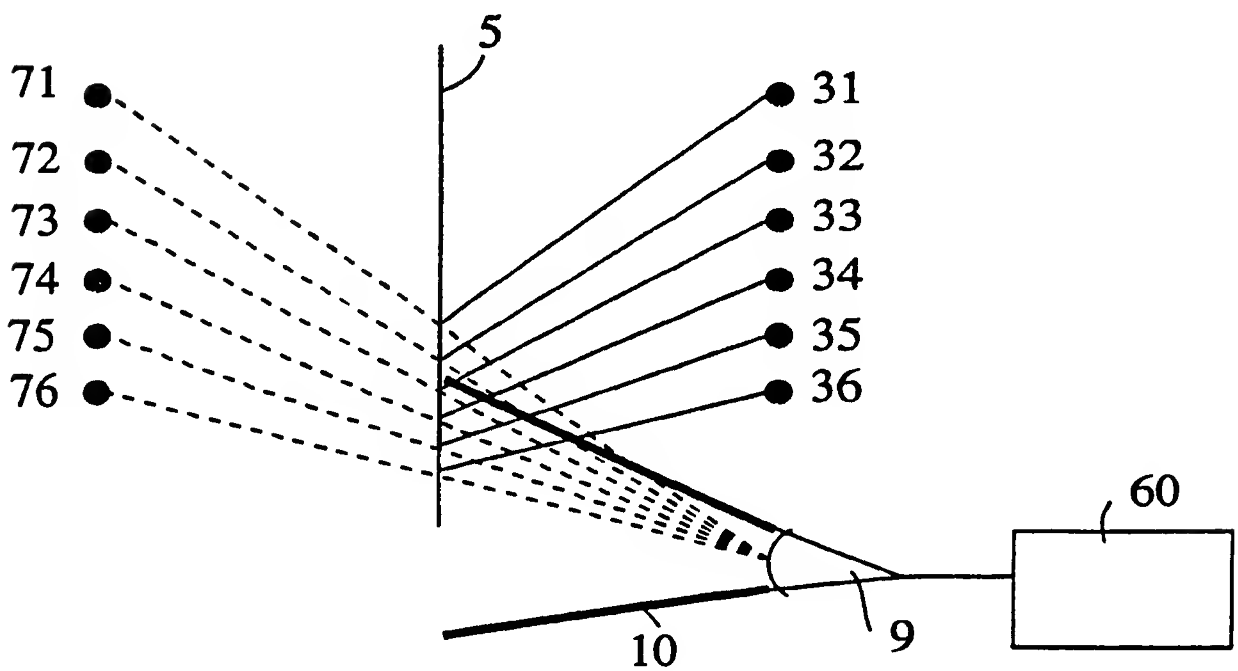

Fig. 4

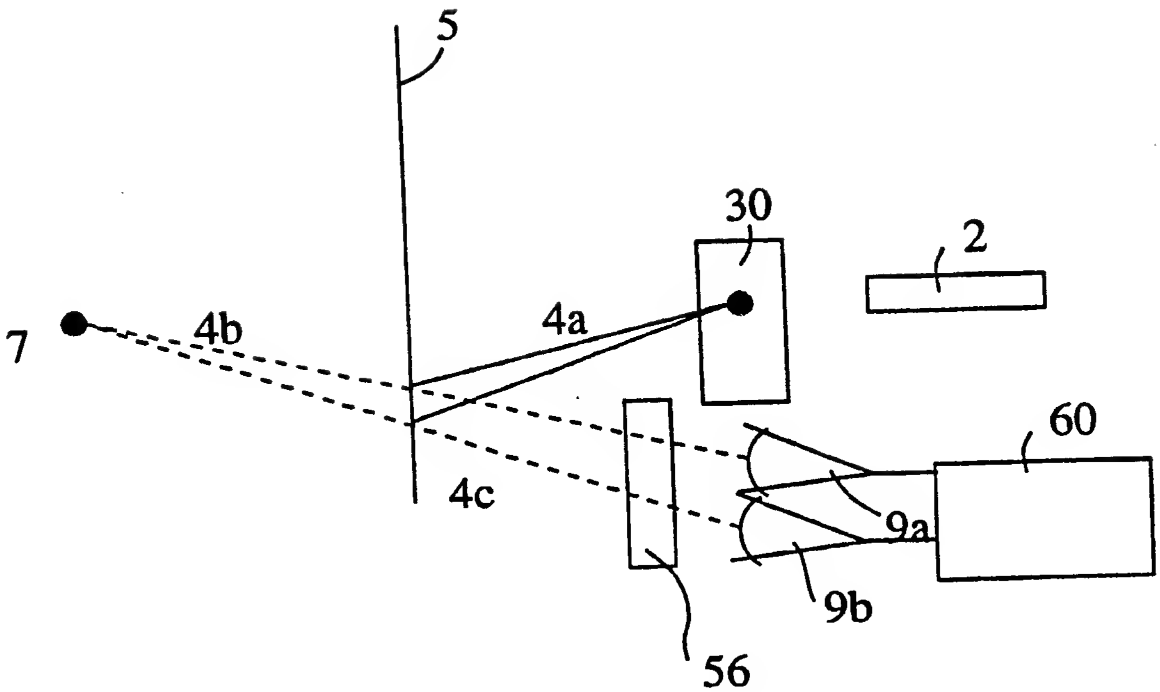

Fig. 5

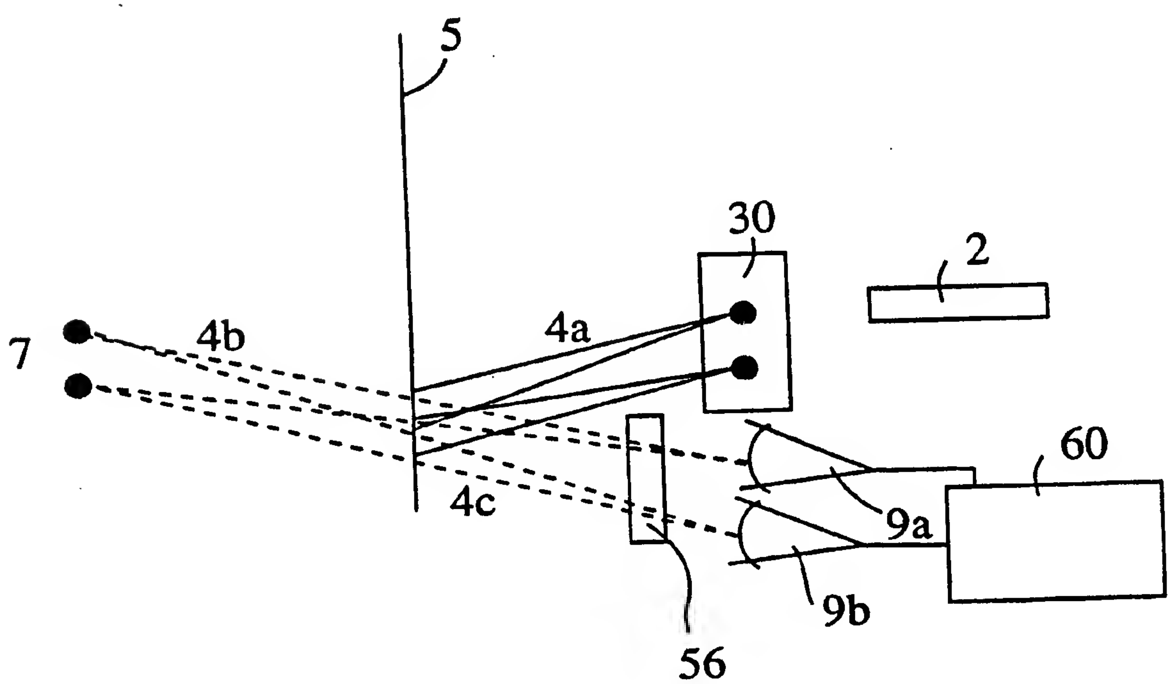

Fig. 6

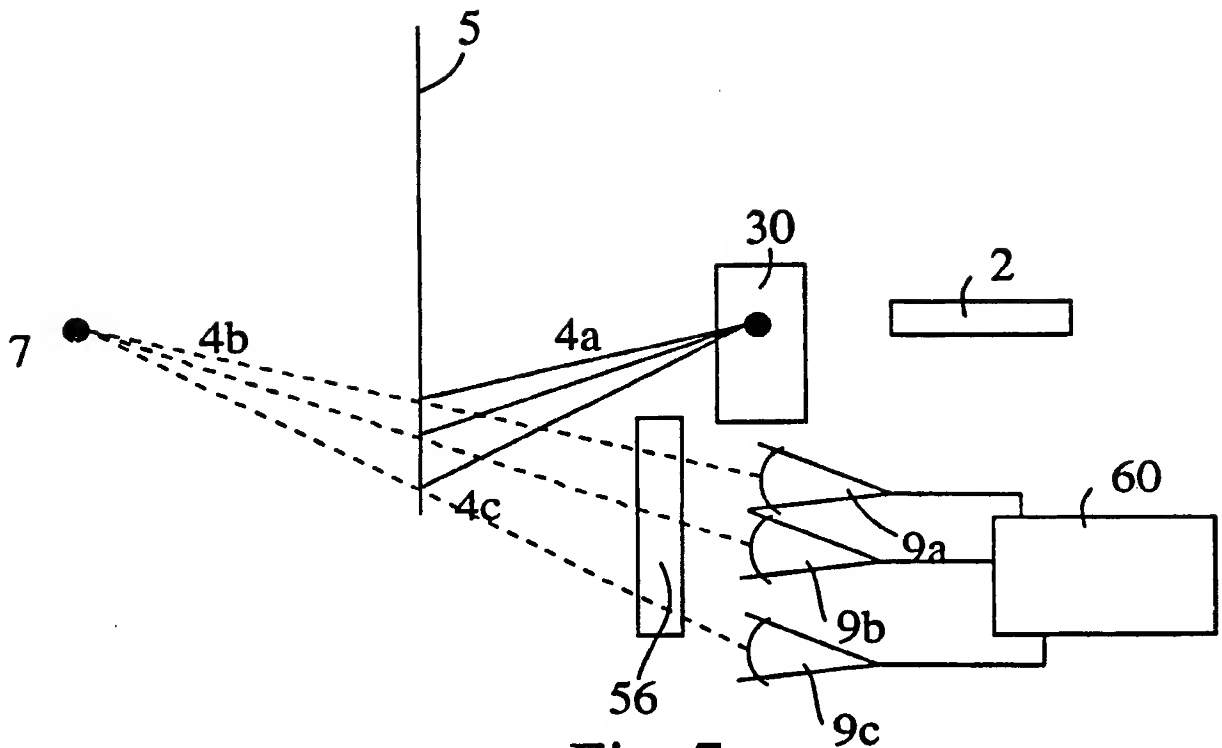

Fig. 7

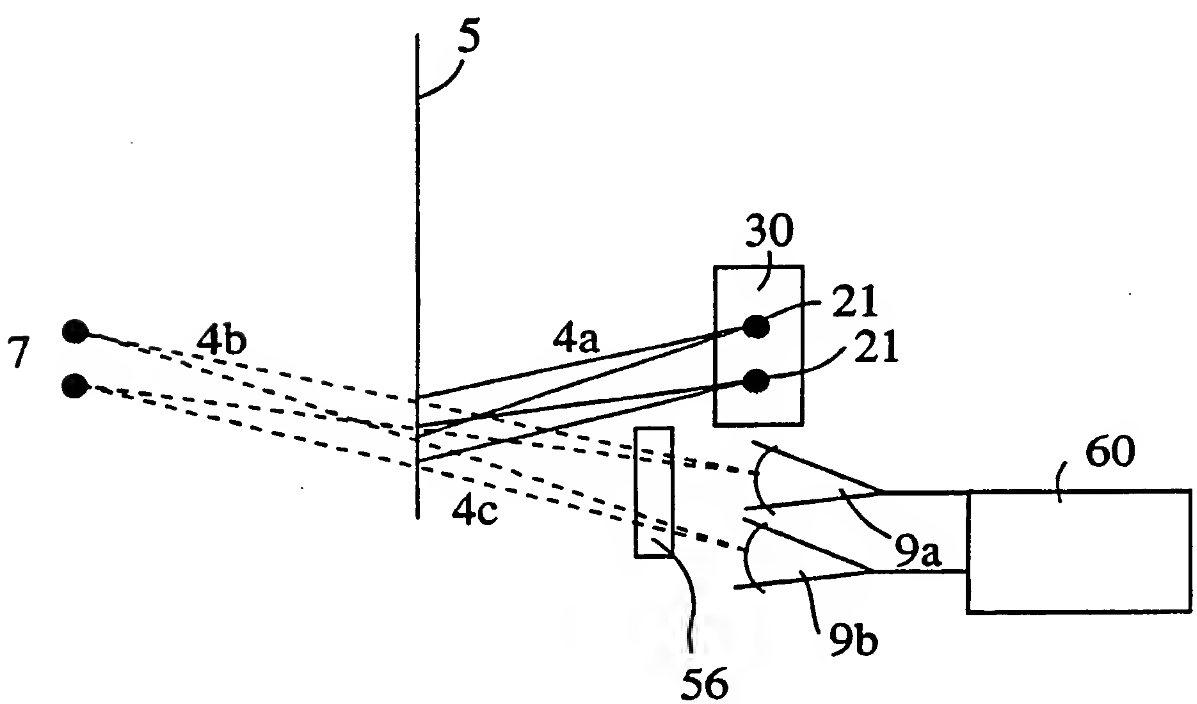

Fig. 8

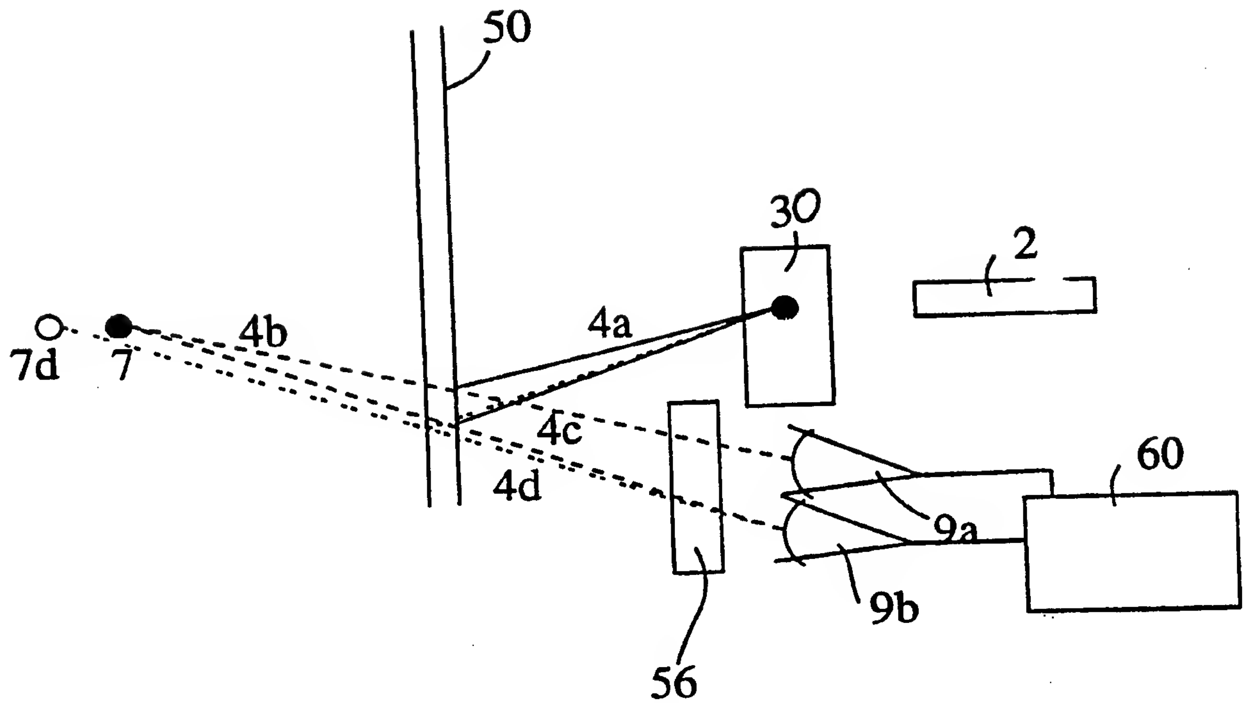

Fig. 9

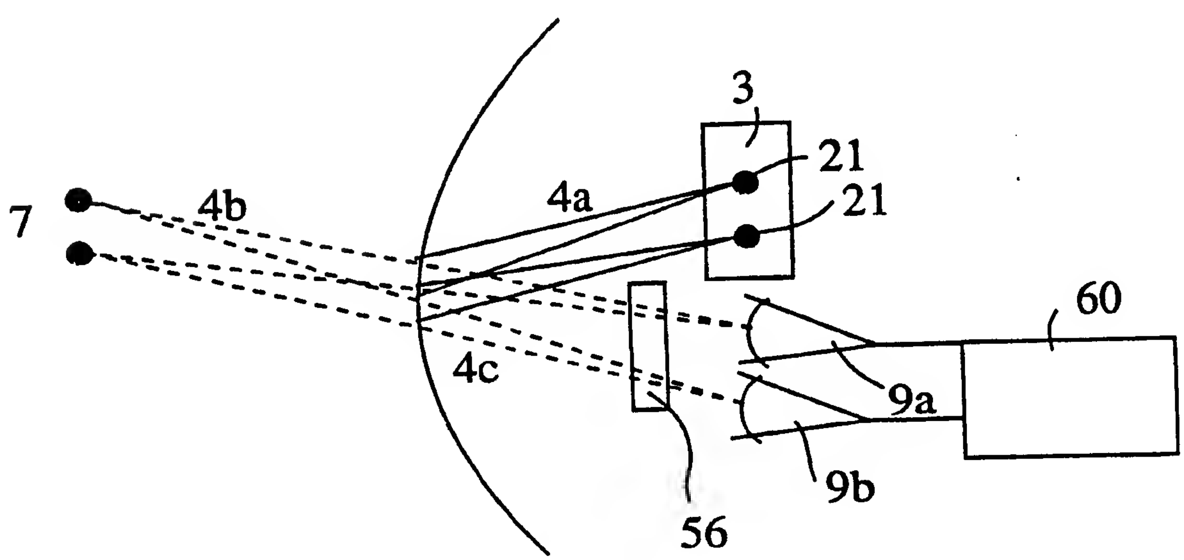

Fig. 10

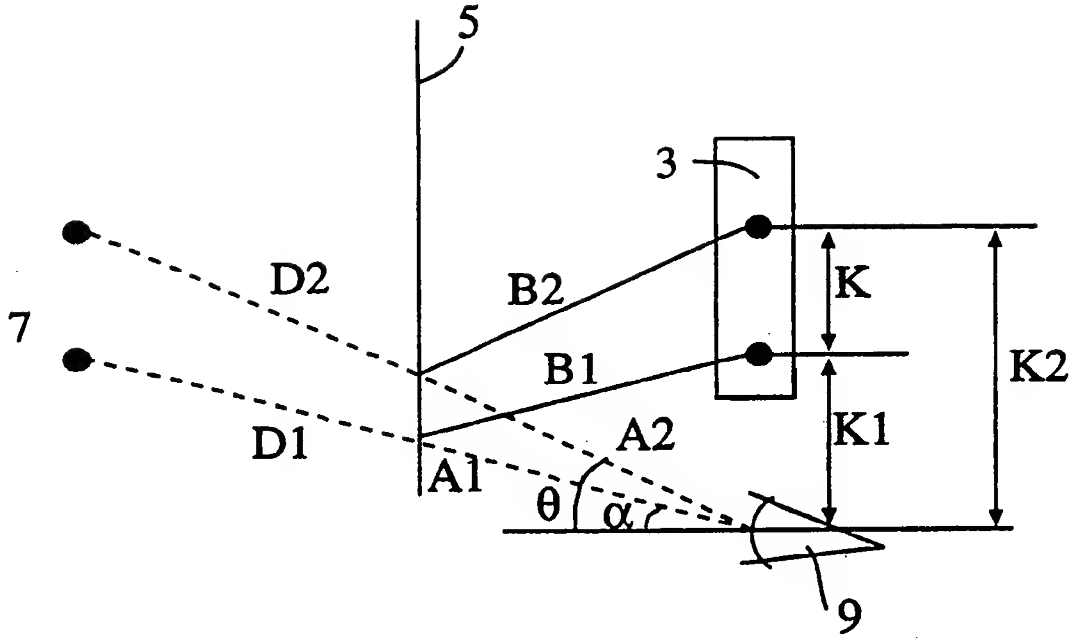

Fig. 11

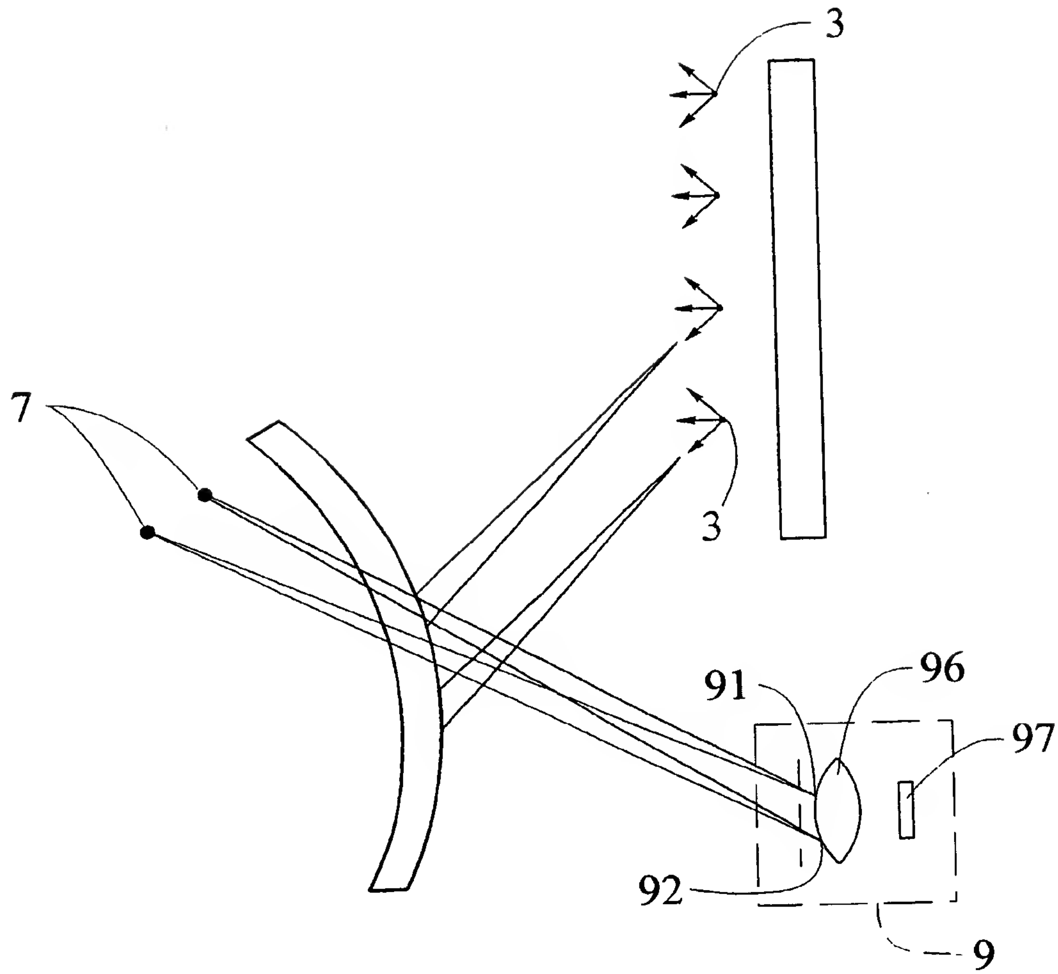

Fig. 12

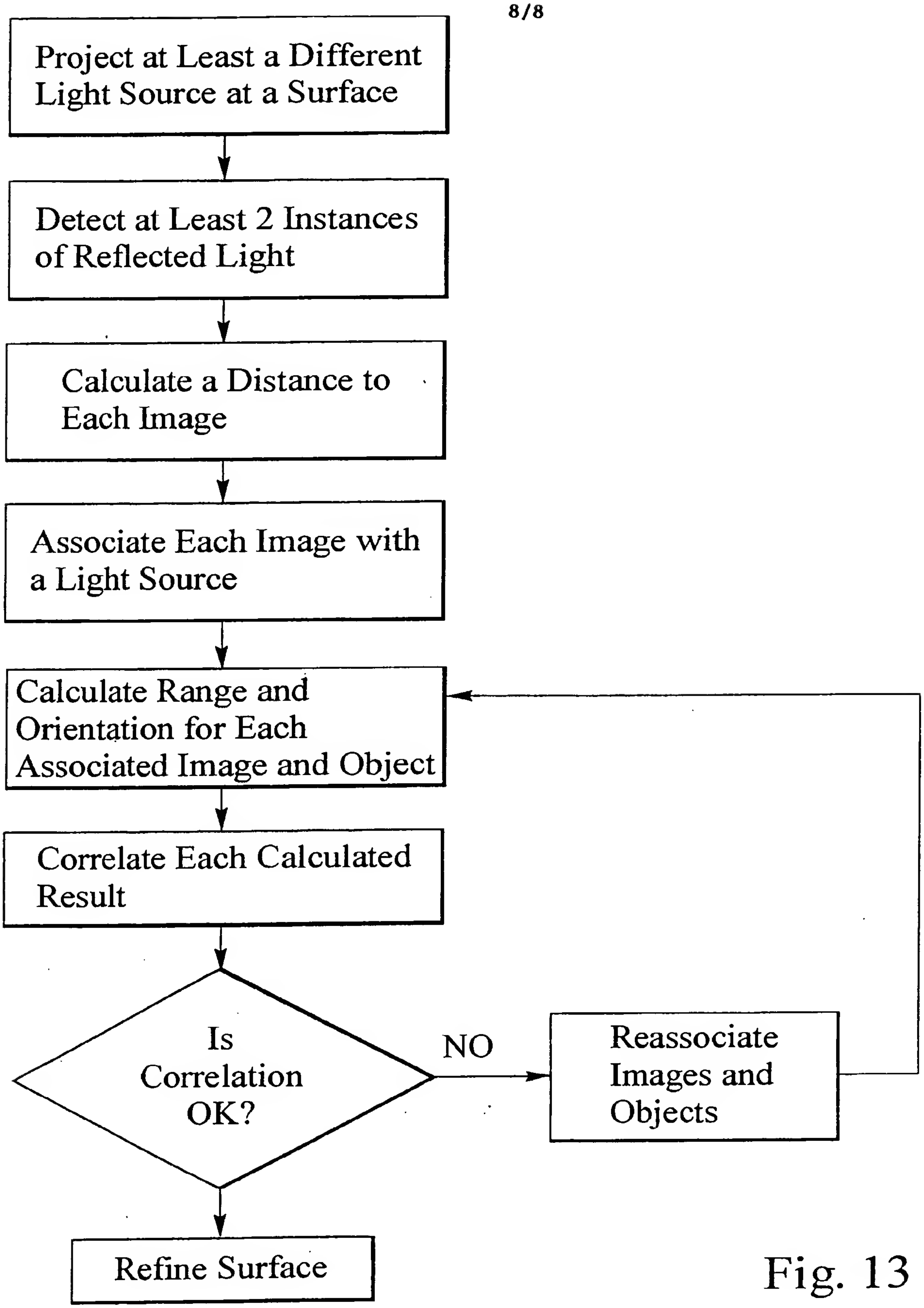
Project at Least a Different Light Source at a Surface
Detect at Least 2 Instances of Reflected Light
Calculate a Distance to Each Image
Associate Each Image with a Light Source
Calculate Range and Orientation for Each Associated Image and Object
Correlate Each Calculated Result
Is Correlation OK?
NO
Reassociate Images and Objects
Refine Surface

Fig. 13

INTERNATIONAL SEARCH REPORT

International Application No
PCT/CA 97/00846

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G01C11/00 G01B11/02

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G01C G01B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 414 517 A (FURUHASHI NAKATOMO) 9 May 1995 see column 4, line 18 - line 30 see column 5, line 14 - line 16 see column 5, line 64 - column 6, line 2 see column 8, line 1 - line 23 see column 8, line 49 - line 56; figures ---	1,6,7, 10,11, 13, 15-18, 20-22,24

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

2

Date of the actual completion of the international search	Date of mailing of the international search report
20 February 1998	26/02/1998
Name and mailing address of the ISA European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Authorized officer Hoekstra, F

INTERNATIONAL SEARCH REPORT

International Application No
PCT/CA 97/00846

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
X	US 5 477 332 A (STONE KENNETH W ET AL) 19 December 1995 see column 5, line 33 - line 38 see column 5, line 55 - line 58 see column 6, line 63 - line 67 see column 8, line 10 - line 27 see column 9, line 7 - line 19 see column 14, line 18 - line 22; figures ---	1,4,10, 11,15, 17,18, 20,23,24
A	US 4 529 316 A (DIMATTEO PAUL) 16 July 1985 see the whole document -----	2,9,12

2

INTERNATIONAL SEARCH REPORT

Information on patent family members

Inte ,onal Application No
PCT/CA 97/00846

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 5414517 A	09-05-95	JP 2034919 C JP 5306915 A JP 7058172 B	28-03-96 19-11-93 21-06-95
US 5477332 A	19-12-95	NONE	
US 4529316 A	16-07-85	NONE	